

PRODUCTION OF GAMMA-RAYS IN BLAZARS

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ABSTRACT.

Some aspects of theory of γ -ray production in blazar type active galaxies are discussed in context of recent observations.

1. Introduction

The multiwavelength spectrum of γ -ray blazars shows two prominent broad bumps, the first one extending from radio up to optical- X-ray energy range, and the second one from X-rays up to at least 30 GeV and in some cases up to ~ 10 TeV. Because many of γ -ray blazars show jets and features of superluminal motion, therefore it is usually assumed that the existence of jets (and accretion disks) are necessary conditions for γ -ray production in these sources. Three general scenarios are discussed in the literature. In the *slow jet model*, the γ -rays are produced in a relativistic blob of particles moving along the jet with the Lorentz factor typically assumed to be of the order of $\gamma \sim 10$ (consistently with the radio observations of superluminal motion although on a parsec distance scale from the center of active galaxies). In the *fast jet model*, it is assumed that particles are moving in the inner jet almost rectilinearly with very high Lorentz factors $\gamma \gg 10$. Particles are accelerated close to the inner disk or in the jet. They are slowed down at the distance of observable radio jets as a result of strong energy losses or isotropization by the perpendicular component of the magnetic field present in the jet. The third scenario, called the *collision model*, propose that γ -ray flares may originate when the compact objects e.g., clouds from the broad line region, massive stars, or debris of close supernova explosions, collide with the jet plasma. The models applying different general scenarios are listed in Table I. In this paper we do not intend to give systematic review of all these models but rather concentrate on theoretical interpretation of recent observational results obtained during last 2 years. The detailed discussion of earlier models has been done in review papers by e.g., Dermer & Schlickeiser (1992), Sikora (1994), Dermer & Gehrels (1995), von Montigny et al. (1995), Schlickeiser (1996), Sikora et al. (1997).

It is usually considered that the low energy bump in the blazar's spectra is caused by synchrotron emission of relativistic electrons. However the origin of the high energy bump is controversial. It may be formed as a result of inverse Compton scattering (ICS)

TABLE I
Models for γ -ray production in AGNs

slow jet models	fast jet models	collision models
Maraschi et al. 1992	Coppi et al. 1993	Dar & Laor 1997
Bloom & Marscher 1996	Bednarek & Kirk 1995	Bednarek & Protheroe 1997a
Inoue & Takahara 1996	Bednarek et al. 1996a,b	Bednarek (this paper)
Mastichiadis & Kirk 1997	Bednarek 1997b	
Mannheim & Biermann 1992	Bednarek 1997a	
Mannheim 1993	Bednarek & Protheroe 1997d	
Bednarek 1993a		
Henri & Pelletier 1993		
Marcowith et al. 1995		
Roland & Hermsen 1995		
Böttcher & Schlickeiser 1996		
Dermer & Schlickeiser 1993		
Sikora et al. 1994		
Sikora & Madejski 1996		
Blandford & Levinson 1995		
Ghisellini & Madau 1996		
Protheroe 1997		
Romanova & Lovelace 1997		

of low energy photons by relativistic electrons , or in a cascade process initiated by relativistic hadrons and/or leptons in the soft radiation and/or magnetic field. The location of the maximum power in the high energy bump differs significantly between different sources. This fact should reflect the basic properties of the mechanism of acceleration of particles and/or the propagation of produced γ -rays in active galactic nuclei (AGN). Therefore we separate all γ -ray blazars in three groups called: MeV, GeV, and TeV γ -ray blazars. Further we discuss these groups separately.

Most of the models mentioned in Tab. 1 assume that electrons play the basic role in production of γ -rays. Only a few of them propose that processes responsible for γ -ray production are of hadronic origin (Mannheim & Biermann 1992, Bednarek 1993a, Coppi et al. 1993, Protheroe 1997, Dar & Laor 1997, Bednarek & Protheroe 1997d). In these models the γ -ray emission has to be accompanied by neutrino emission allowing their straightforward testing by future large neutrino detectors.

2. GeV γ -ray blazars

About 50 active galaxies has been detected by EGRET detector above ~ 30 MeV (von Montigny et al. 1995). Most of these sources are flat spectrum radio quasars, many of them show feature of superluminal motion, and jets aligned at small angles towards the observer's line of sight. The γ -ray emission probably consists of two components from which the first one is persistent but on a low level and the second one is highly variable on a time scales from a part of a day up to weeks and months. The γ -ray spectra of blazars are usually interpreted as a single power law with differential spectral index laying in

the range between 1.4 and ~ 3 . There are some evidences that the spectra observed during the flare states are flatter in comparison to the low states. The spectra show also the spectral break at MeV energies and there is a weak evidence of the spectral cut-off above a few GeV (Pohl et al. 1997). The γ -ray luminosity of these sources dominate in many cases the luminosity observed in other energy bands.

Recently a spectacular γ -ray flare has been observed from PKS 1622-297 (Mattox et al. 1997). This source shows the most rapid change of γ -ray flux (doubling time is less than 3.8 hours) and extremely high peak luminosity corresponding to isotropic luminosity of 2.9×10^{49} erg s $^{-1}$. If this emission is produced in a relativistic jet then the minimum Doppler factor of ~ 8.1 is required in order to avoid the absorption of γ -rays by co-spatially produced X-rays. The parameters of the flare observed from PKS 1622-297 allows us to estimate the energy density in the region of γ -ray production. Let us assume that the emission region is homogeneous and has a form of a disk with the thickness r_γ and radius κr_γ (see Kirk 1997). It moves towards the observer located at the jet axis with the Lorentz factor γ . The energy density in the γ -ray emission region is

$$\rho = \frac{L_\gamma t_v \Delta\Omega}{\pi r_\gamma^3 \kappa^2} \approx 7 \times 10^{-34} L_\gamma t_v^{-2} \gamma^{-5} \kappa^{-2} \text{ erg cm}^{-3}, \quad (1)$$

where L_γ is measured γ -ray luminosity (for the isotropic case), t_v is the variability time scale, $\Delta\Omega$ is the solid angle in which these γ -rays are emitted. We assume $\Delta\Omega \approx 1/4\gamma^2$. The thickness of the emission region, $r_\gamma \approx \gamma t_v c$, is estimated based on the time flight arguments, and c is the velocity of light.

This energy may be transported from the central engine in the form of the kinetic energy of the jet plasma or in the form of the Poynting flux (see e.g. Romanova & Lovelace 1997). Assuming this second possibility, and by comparing Eq. (1) with the required energy density of the magnetic field, we obtain lower limit on the magnetic field strength in the emission region as a function of the jet Lorentz factor

$$B \geq 10^{-16} L_\gamma^{1/2} t_v^{-1} \gamma^{-5/2} \kappa^{-1} \text{ G}. \quad (2)$$

If we put into this formula the parameters observed during the flare in PKS 1622-297, we get the magnetic field strength in the emission region as a function of its Lorentz factor which is for example: $B > 250/\kappa$ G if $\gamma = 8$, $B > 25/\kappa$ G if $\gamma = 20$, and $B > 0.4/\kappa$ G if $\gamma = 100$. If the value of parameter κ is close to one, the conclusion from these simple considerations is the following, either

- the jets are fast with the Lorentz factor $\gamma \sim 100$, or
- the γ -rays are produced rather close to the central engine, or
- the energy is transferred in the jet mainly in the form of kinetic energy of the jet plasma.

In the next section we discuss briefly models proposed as possible explanations of γ -ray production in GeV blazars.

2.1. Models for γ -ray production in GeV blazars

Earlier models constructed with the purpose to explain the GeV γ -ray emission from blazars use a soft radiation of external or internal origin in respect to the jet as a target for relativistic particles. The target radiation of synchrotron origin, produced internally, is postulated by the synchrotron self-Compton (SSC) models (e.g. Maraschi et al. 1992, Bloom & Marscher 1996, Inoue & Takahara 1996, Mastichiadis & Kirk 1997), and by proton initiated cascade model (Mannheim & Biermann 1992). The external radiation coming directly from the accretion disk is used as a target for particles accelerated in the jet by Dermer & Schlickeiser (1993). The disk radiation which is quasi-isotropised by scattering on the matter distributed around the disk is applied by Sikora et al. (1994) and Blandford & Levinson (1995). The interaction of particles with the quasi-isotropised jet radiation is proposed by Ghisellini & Madau (1996). It is argued by Dermer & Schlickeiser (1994) that the γ -ray production by electrons which scatter direct disk radiation is more efficient close to the accretion disk, but at further distances the scattering of isotropized disk radiation may dominate. It seems that the recent observations of flares varying on a very short time scales favour the production of γ -rays rather close to the disk, provided that the jet is slow ($\gamma \sim 10$). However if the γ -rays are really produced by scattering the quasi-isotropic radiation at farther distances from the disk, then the assumption on a slow jet is not further relevant, and better description of the distribution of particles in the jet is given by the fast jet model. The problem on the origin of soft target photons can become more clear if some γ -ray blazars (of BL Lac type) would show strong X-ray flares without accompanied TeV γ -ray flares. Such behaviour could be interpreted that the electrons are accelerated to sufficiently high energies to produce TeV γ -rays but these energetic photons are absorbed by quasi-isotropic radiation. Different models proposed up to now need different conditions in the source region. Therefore different radiation mechanisms may in fact operate in this same source but the observed spectrum may be dominated by only one or two of them. The above mentioned models and their relevance to the observations has been discussed already in the reviews mentioned in the Introduction. Further in this subsection we describe the models which were not considered in the previous reviews.

The γ -ray spectra observed from blazars may be also formed as a result of cascades developing in the jet or close to the surface of an accretion disk. Such interpretation has been considered in the context of the Compton GRO observations of blazars by Coppi et al. (1993), Bednarek & Kirk (1995), Bednarek (1997a) and Bednarek & Protheroe (1997d). Coppi et al. assumed that electrons (or protons) are injected instantaneously at certain distance, measured along the jet, with very high Lorentz factors ($> 10^4$). They analyze the cascade developing in the disk radiation applying different models for the disk emission. The approach of Bednarek & Kirk (1995) is different since in their work the importance of interaction of particles, with the radiation coming from the thick accretion disk, during acceleration in the jet is discussed. The cascade in the radiation and electric fields is analyzed. It is found that in certain conditions the energy of particles gained from the electric field can be very efficiently transferred to γ -rays.

Another cascade scenario is proposed by Bednarek (1997a) and Bednarek & Protheroe (1997d). Following the model for acceleration of particles close to the accretion disk sur-

face (Haswell et al. 1992), we consider the cascade developing in the disk radiation and magnetic fields above the disk surface. Particles can be accelerated close the disk surface in strong electric fields, induced in reconnection of magnetic fields which are additionally multiplied by the disk differential rotation (Haswell et al. 1992). Extremely high potential drops, of the order of $\sim 10^{20-21}$ eV, can appear according to such a model. Both types of particles (electrons and protons) can be accelerated in this same source in the reconnection regions of opposite polarity. Bednarek (1997a) analyzes the cascades initiated by primary electrons and defines the conditions for such cascades to occur. It is shown that for strong disk radiation field and slightly curved reconnection region the acceleration of electrons is saturated by their curvature energy losses. This process transfers very efficiently energy from electrons to extremely high energy γ -rays. These γ -ray photons are able to initiate cascade in the magnetic field above the reconnection region via magnetic e^\pm pair production and quantum synchrotron radiation. When the e^\pm magnetic pair cascade becomes inefficient, the absorption of γ -rays in the disk radiation and the synchrotron emission of secondary e^\pm pairs determines the formation of the γ -ray spectrum escaping from active galaxy. The γ -ray spectra, obtained in such a model, are consistent with the observations of GeV γ -ray blazars. They can extend through the TeV γ -ray energy range if the disk temperature is relatively low.

The cascades initiated by protons accelerated in the reconnection regions follow partly different scenario (Bednarek & Protheroe 1997d). The curvature losses of protons are much smaller than these ones suffered by electrons, therefore protons are accelerated without significant losses in a relatively small scale reconnection regions. Depending on the parameters of the model (magnetic field strength, temperature of the local disk radiation and length of the acceleration region), protons can be injected into the disk radiation with energies corresponding to the maximum potential drop, or with energies limited by the condition for saturation of the electric field by the products of the cascades initiated by secondary e^\pm pairs produced in collisions of protons with radiation. If the radiation field in the acceleration region is strong then the secondary e^\pm pairs can take most of the energy from the electric field and further processes should occur as in the case considered by Bednarek (1997a). The conditions for specific scenarios mentioned above are discussed in detail in Bednarek & Protheroe (1997d). The protons, injected from the acceleration region into the disk radiation with energies corresponding to the full available potential drop, escape to the surrounding galaxy (if disk radiation is weak) or lose energy mainly on pion production in collisions with the disk photons. The e^\pm pairs from decay of pions are energetic enough to initiate magnetic e^\pm pair cascade. For the strong disk radiation the γ -rays are absorbed in the soft radiation field and the emerging γ -ray spectra show cut-offs at ~ 100 GeV, consistently with the observations of GeV γ -ray blazars but not with the observations of TeV γ -ray blazars. Since the charged pions are produced in hadronic collisions, this γ -ray emission is accompanied by the neutrino emission with fluxes comparable to the γ -ray fluxes. The characteristic energies of neutrinos are of the order of $\sim 10^{17}$ eV. We have computed the neutrino power spectrum which should accompany the strong γ -ray flare observed from 3C 279 during June '91, and have found that the expected number of neutrinos observed during the 10 day flare should give on average coincident one neutrino event in 1 km^3 detector with the angular resolution of one degree. This rate is orders of magnitudes above the

atmospheric neutrino background in such detector. Therefore the GeV γ -ray blazars are expected to emit detectable neutrino fluxes in contrary to the TeV γ -ray blazars.

The production of high energy radiation in collisions of particles with matter seems to be less likely at present because of the problems with finding dense enough target. However, in principle, particles might interact with the matter accumulated in the thick accretion disk as discussed by Bednarek (1993a) or with the dense clouds from the broad emission line region (Dar & Laor 1997).

The interactions of relativistic particles with matter of the host galaxy, containing blazar type AGN, may also contribute to the low level γ -ray emission. It seems obvious that because of the violent activity of the nucleus, the density of relativistic particles in the volume of galaxy containing active nucleus has to be orders of magnitude higher than in our own Galaxy. Provided that the relativistic particles escape efficiently from the acceleration regions in the jet and a significant part is accumulated in the galaxy by galactic magnetic fields, we should expect low level of γ -ray emission e.g., from nearby radio galaxies, even if they do not show characteristic features of blazars. The persistent γ -ray luminosity of such radio galaxy can be estimated by using simple formula

$$L_{\gamma}^{\text{RG}} \approx 0.2c\sigma_{\text{pp}}\tau_{\text{b,es}}n_{\text{G}}\eta L_{\text{b}} \approx 1.8 \times 10^{-16}\tau_{\text{b,es}}n_{\text{G}}\eta L_{\text{b}}, \quad (3)$$

where σ_{pp} is the proton-proton cross section, c is the velocity of light, $\tau_{\text{b,es}}$ is the characteristic residence time of relativistic protons in the host galaxy, which is taken to be equal to the activity phase, τ_{b} , of the blazar type AGN, or to the escape time, τ_{es} , of the protons from the host galaxy. n_{G} is the average density of background matter in the host galaxy, η is the efficiency of accumulation of the particles accelerated in the jet by the host galaxy, and L_{b} is the power in particles accelerated in the jet. For example, taking $n_{\text{G}} = 1 \text{ cm}^{-3}$, $\tau_{\text{b,es}} = 10^7$ years, and $\eta L_{\text{b}} = 10^{42} \text{ erg s}^{-1}$ (e.g. $\eta = 0.01$ and $L_{\text{b}} = 10^{44} \text{ erg s}^{-1}$), then the persistent γ -ray luminosity of the radio galaxy is $L_{\gamma}^{\text{RG}} \approx 5 \times 10^{40} \text{ erg s}^{-1}$. This is consistent with not variable γ -ray luminosity ($\sim 8.3 \times 10^{40} \text{ erg s}^{-1}$, Thompson et al. (1995)) from the γ -ray source 2EG J1324-4317. This source is coincident with the closest radio galaxy Cen A (supposed to be misaligned blazar).

3. TeV γ -ray blazars

Two BL Lac type blazars, Mrk 421 and Mrk 501, has been detected at TeV γ -ray energies by the Whipple Observatory (Punch et al. 1992, Quinn et al. 1996). These discoveries are confirmed independently by other experiments (Petry et al. 1996, Breslin et al. 1997, Barrau et al. 1997). The third source of this type, 1E2344, has been recently detected with low significance (Weekes 1997). The observed emission has a form of very strong flares on time scales from days (Buckley et al. 1996, Breslin et al. 1997) up to a part of hours (Gaidos et al. 1996, Aharonian et al. 1997). The spectrum of Mrk 421 is flat in the low state with differential spectral index $\sim 2.25 \pm 0.19 \pm 0.3$ between 0.4 – 4 TeV (Mohanty et al. 1993). The spectrum in the high state is consistent with that one observed in the low state and extends up to at least 8 TeV (Krennrich et al. 1997). The γ -ray spectra of BL Lac type blazars extend probably to much higher energies. A small evidence (6.5σ) of the γ -ray emission above ~ 50 TeV from some nearby BL

Lacs has been also reported. Between them Mrk 421 has a significance of 3.8σ (Meyer & Westerhoff 1996). Similarly the spectrum of Mrk 501 extends up to at least 10 TeV in a high state with the differential spectral index $2.49 \pm 0.11 \pm 0.25$ (Aharonian et al. 1997). The TeV γ -ray flares from Mrk 421 are simultaneous with the X-ray flares measured by the ASCA satellite (Buckley et al. 1996, Macomb et al. 1995).

One of the first type of models in which the production of γ -rays in active galaxies has been discussed is so called "synchrotron self-Compton model" (SSC). In the simplest version of this model (homogeneous model) the low energy part of the spectrum (from radio to X-rays) and the high energy part (from X-rays to γ -rays) are produced in this same homogeneous and isotropic region (a blob) by a single population of electrons. The electrons, accelerated by a shock moving in the jet, lose energy on synchrotron process in the blob magnetic field and on inverse Compton scattering (ICS) of these synchrotron photons to γ -ray energies (e.g. Inoue & Takahara 1996, Bloom & Marscher 1996, Mastichiadis & Kirk 1997). Such a picture naturally explains synchronized variability at different photon energies. Application of this model to the observations of TeV γ -ray emission from Mrk 421 has been recently tested by Bednarek & Protheroe (1997c). Based on the detected variability time scales of TeV γ -ray emission, observations of coincident flares in X-rays and TeV γ -rays, and the observed multiwavelength photon spectrum of Mrk 421, the constraints has been placed on the allowed parameter space (magnetic field in the emission region and its Doppler factor) for the homogeneous SSC model. For the 1 day flare, the magnetic field in the blob has to be limited to the range $\sim 0.025 \div 0.15$ G, and the corresponding Doppler factors to the range $\sim 20.5 \div 10.7$. For the 15 min flare these limits are following: $\sim 0.4 \div 1.3$ G, and $\sim 37.6 \div 24..$ The spectra calculated in terms of the homogeneous SSC model, for the marginal values of the allowed parameter space, are consistent with the available spectral information above ~ 1 TeV in the case of a flare varying on a 1 day time scale. However for recently reported very short 15 min flare, the calculated spectra are significantly steeper, suggesting that the homogeneous SSC model has problems with describing relatively flat spectra observed up to ~ 10 TeV.

The problems met by the homogeneous SSC model might be avoided if the assumption on spherical geometry of the blob is released. Recently Kirk (1997) has proposed that the blob of relativistic electrons should have rather a form of a thin plane with the ratio, κ , of the thickness to broadness much lower than one. For the case of 15 min flare from Mrk 421, this value has been estimated as equal to $\kappa \approx 0.03$, based on the assumption that the variability time scale of synchrotron emission is determined by the cooling time of electrons (see also Takahashi 1996). However in the case when the period of activity of acceleration mechanism determines the flare timescale (Bednarek & Protheroe 1997c), than the values of magnetic field and aspect ratio κ , estimated by Kirk (1997), becomes a lower limit.

More complicated inhomogeneous SSC models in which the radiation at different energies is produced in different regions of the jet (e.g. Ghisellini et al. 1985, Maraschi et al. 1992) are also proposed. They are not constrained by the arguments discussed above. However they predict the time delay between different photon energies which should be observed.

Another way of constraining the parameters of the emission region has been proposed

by Bednarek (1996). In the standard model of the central engine of active galaxy, the massive black hole is surrounded by an accretion disk whose strong thermal radiation can be directly observed in some objects (e.g. 3C 273). For reasonable accretion rates and central black hole masses, this radiation is strong enough to prevent the escape of high energy γ -rays if they are produced in a blob moving along the jet (Bednarek 1993b, Becker & Kafatos 1995, Zhang & Cheng 1997). The γ -ray photons with energies above the threshold for e^\pm pair production may escape from the disk radiation only from distances greater than so called the radius r_γ of the " γ -ray photosphere", which is defined by the condition that the optical depth for the absorption of γ -rays in the disk radiation is equal to one (e.g. Blandford & Levinson 1995, Bednarek 1996).

In the case of Mrk 421 the disk emission is not directly observed. However the parameters of the disk in this source can be estimated on statistical grounds, based on the observed correlation between the disk luminosity and the radio jet luminosity at 5 GHz (Falcke et al. 1995). Such procedure, carried out for Mrk 421 (Bednarek 1996), allows to estimate the radius of the γ -ray photosphere for the γ -ray photons with maximum energies observed from Mrk 421. This information combined with the observations of variability time scale of radiation emitted by the blob, together with the assumption on the spherical symmetry of the blob, and the information on the relativistic motion of the blob along the jet, derived from superluminal motion in Mrk 421 ($\beta_{\text{app}} = 3.8$ for the Hubble constant $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, Zhang & Baath (1990)), allows us to put constraints on the blob Lorentz factor as a function of the inner accretion disk radius (for details see Bednarek 1996). Fig. 1 shows the lower limits on the blob Lorentz factor in Mrk 421 for the cases of γ -ray flares variable on a time scale of $t_v = 1$ day during which photons are emitted with energies $E_\gamma = 50 \text{ TeV}$ (full curve) and for $t_v = 15 \text{ min}$ and photon energies $E_\gamma = 8 \text{ TeV}$ (dot-dashed curve) and $E_\gamma = 50 \text{ TeV}$ (dashed curve). The limits on the jet Lorentz factor, derived for reasonable disk inner radii, are of the order of a few tens, reaching ~ 100 for the high mass black holes. Similar analysis can be performed for other γ -ray emitting blazars with the features of superluminal motion. For example in the case of QSO 1633+382, which is the EGRET detected γ -ray blazar at large distance, the constraints are also more restrictive than obtained on the base of superluminal motion alone (Bednarek 1996).

3.1. Quasi-periodic modulation of TeV γ -rays ?

The multiwavelength campaign has been established for the observations of Mrk 421 during May 1995. The obtained optical, extreme UV, X-ray and TeV γ -ray light curves shows very interesting behaviour (see Fig. 3 in Buckley et al. 1997). At least three, and possibly four, maxima and corresponding minima, separated by a ~ 3.3 day interval, are clearly evident in the TeV γ -ray and optical light curves superimposed on a broader ~ 1 week high activity state (see Bednarek & Protheroe 1997b). The X-ray light curve shows also quasi-periodicity, although on a day time scale, as noted by Takahashi et al. (1996) and Schubnell (1997).

This possible quasi-periodicity is not easily explained in the models which assume that high energy emission comes from a relativistic blob moving along the jet (see models mentioned in the Introduction). However most of the extreme UV and X-ray emission

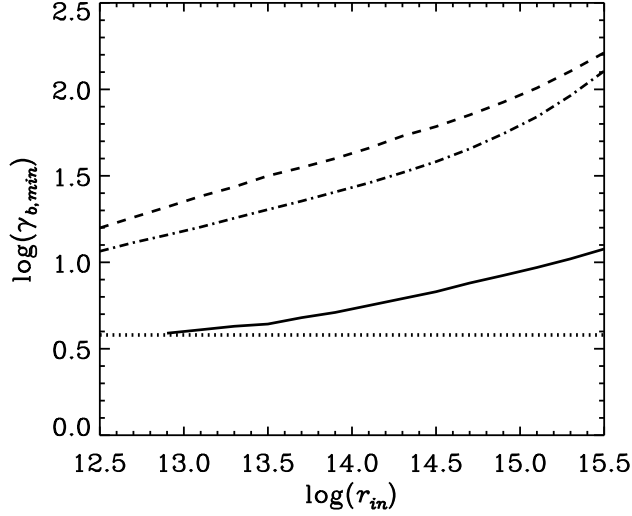


Fig. 1. Lower limits on the Lorentz factor of the blob moving in the jet of Mrk 421 are shown, assuming that the γ -ray flux varies on a time scale: $t_v = 1$ day and photons are emitted with energies $E_\gamma = 50$ TeV (full curve); $t_v = 15$ min and $E_\gamma = 8$ TeV (dot-dashed curve) and $E_\gamma = 50$ TeV (dashed curve). The dotted curve shows the limit obtained from observations of the superluminal motion alone.

can originate in a relatively small hot spot rotating on surface of the inner accretion disk (Bednarek & Protheroe 1997b). If the TeV emission originates in the jet above the disk then the selective absorption of TeV γ -rays in the hot spot radiation can induce quasi-periodic modulation of TeV signal with the period corresponding to the orbital period of the hot spot. Bednarek & Protheroe (1997b) has computed the optical depth for TeV γ -rays in such scenario and put the limits on the disk radiation below which modulation effects are not overwhelmed by the absorption in the whole disk radiation. For Mrk 421, the possible ~ 3.3 day variability could be explained if the mass of the central black hole in this source is less than $6 \times 10^8 M_\odot$ (in the case of the Schwarzschild black hole) or $10^{10} M_\odot$ (Kerr black hole). The model predicts also small time delay between X-ray and γ -ray emission caused by the different path lengths to the observer from the emission regions of these radiations.

3.2. Interactions of clouds and stars with AGN jets and γ -ray production.

Dar & Laor (1997) proposed that TeV γ -ray flares may originate in hadronic collisions of a highly collimated relativistic proton beam (Lorentz factors up to $\sim 10^4$) with small, dense clouds entering the jet. In this model the high level of variability of TeV γ -ray flux in comparison with GeV γ -ray flux is caused by stronger collimation of TeV γ -rays in respect to GeV γ -rays if they originate in hadronic collisions. This fact was previously noted and discussed in astrophysical context by Bednarek et al. (1990). However, for

typical parameters of the clouds in AGNs (cloud temperature $\sim 10^4$ K, density $\sim 10^{12}$ cm $^{-3}$, and radius $\sim 10^{13}$ cm), the effects of collisionless excitation of plasma waves by relativistic electron-proton beams may become very efficient energy loss mechanism specially for beams with the Lorentz factors below $\gamma_b \sim 100$ (Rose et al. 1984). Therefore the GeV γ -rays can not be produced efficiently in such a model, since protons with $\gamma_b \leq 100$ are not able to penetrate over distances comparable to the typical cloud radius. Dar & Laor (1997) has noted that secondary e^\pm pairs from decay of charged pions produce synchrotron X-rays and MeV - GeV γ -rays in inverse Compton process. However, in such a case we should expect the correlation between X-rays and MeV-GeV γ -rays which is not observed. The X-ray emission is correlated with the TeV γ -ray emission in Mrk 421 (Buckley et al. 1997).

The collisions of objects with the jet in AGNs can be an attractive mechanism of γ -ray production in another scenario proposed recently by Bednarek & Protheroe (1997a). It seems obvious that many stars must collide with the jet plasma since the processes of star formation in the central regions of active galaxies are very efficient. For example, the central dense stellar core in the Galactic Center is $\sim 10^7 - 10^8$ stars pc $^{-3}$ (Eckart et al. 1993), and the central total mass density has been estimated on $\sim 10^{9.8} M_\odot$ pc $^{-3}$ (Eckart & Genzel 1996). In M32 the central stellar density exceeds $10^7 M_\odot$ pc $^{-3}$ (Lauer et al. 1992). If the massive star with a strong stellar wind (e.g. Wolf-Rayet or OB type) enters the jet then as a result of stellar wind – jet plasma collisions a double shock structure should form at some distance from the star surface. The electrons accelerated by such shocks produce X in synchrotron process and γ -rays by scattering soft thermal photons coming from the massive star. This high energy emission is likely to be collimated along the shock front since it is expected that the distribution of electrons accelerated by relativistic and oblique shock can be highly anisotropic (Kirk & Heavens 1989, Ostrowski 1991). The γ -ray spectra computed in terms of such a model can extend through the TeV energy range and the expected variability time scales are consistent with the observations of a two week high level of TeV γ -ray emission observed in Mrk 421 (see Bednarek & Protheroe 1997a). Moreover this model suggest possible another explanation of quasi-periodic oscillations of TeV γ -ray flux on a time scale of days as due to the rotation of a massive star. Rotation effect causes periodic variation of the magnetic fields in the region of the shocks and consequently influences the acceleration efficiency of electrons.

3.3. Explosions of supernovae close to the jet

As we have mentioned above the density of massive stars in the central region of active galaxy ($\sim pc$) can be very high. Therefore it is expected that the supernova rate in central parsec is high. The expanding supernova shell can significantly compress the jet plasma if the explosion occurs relatively close to the jet. We can estimate this distance by comparing the pressure of the material in the supernova shell with the pressure of the jet plasma. The supernova pressure is

$$P_{SN} \approx \frac{3M_{SN}v_{SN}^2}{4\pi r_{SN}^3} \approx 1.8 \times 10^{-6} L_{50} r_1^{-3} \text{ erg cm}^{-3}, \quad (4)$$

where $L_{50} = 10^{-50} M_{SN} v_{SN}^2 / 2$ is the supernova kinetic power in units of 10^{50} erg, M_{SN} is the mass of the shell and v_{SN} is its velocity. r_1 is the radius of the shell in parsecs. By comparing supernova shell pressure with the jet plasma pressure (see Eq. 1 in Bednarek & Protheroe 1997a) we can estimate

$$r_1 \leq 0.01 L_{50}^{1/3} L_{46}^{-1/3} \theta_5^{-2/3} l_1^{-2/3} \text{ pc}, \quad (5)$$

where L_{46} is the jet power in units of 10^{46} erg s $^{-1}$, θ_5 is its opening angle in units of 5° , and l_1 is the distance in parsecs. Note that if r_1 is of the order of l_1 then all supernovae exploding below l_1 has to interact strongly with the jet. This condition ($r_1 \approx l_1$) defines the distance l_{int} below which all supernovae create strong shocks in the jet,

$$l_{int} \approx 0.06 L_{50}^{1/5} L_{46}^{-1/5} \theta_5^{-2/5} \text{ pc}. \quad (6)$$

Above l_{int} only a part of exploding supernovae, of the order of $\sim r_1^2 / 4l_1^2$, create strong shocks in the jet. As a result of such interaction a large scale ($> 10^{17}$ cm) relativistic shock can be formed in the jet plasma with the magnetic field strength on the front significantly higher than expected in isolated supernovae, because of the stronger magnetic field strength in the jet. In such scenario the particles can reach energies

$$E_{max} \approx \chi e c B r_{sh}, \quad (7)$$

where χ is the shock acceleration efficiency, which is of the order of $\sim 4 \times 10^{-2}$ for relativistic shocks (Protheroe 1997), e is the elemental electric charge, and c is the velocity of light. For example if the magnetic field in the jet is $B = 1$ Gs and $r_{sh} = 10^{17}$ cm, then particles can reach energies of the order of $E_{max} > 10^{18} Z$ eV, where Z is the atomic number of accelerated nuclei. Note that Z can be very high since a lot of very heavy nuclei are expected to originate during the supernova explosion.

If the shell front is not uniform but contains smaller scale debris, then the number of shocks in the jet should be created and the particles accelerated by them may interact with the accretion disk radiation (direct or reprocessed by a matter surrounding the disk) producing γ -ray photons. This picture is complementary with the model of γ -ray production in AGNs considered by Bednarek, Kirk & Mastichiadis (1996a,b).

4. MeV γ -ray blazars

The COMPTEL telescope on the Compton GRO has detected a few blazars whose power spectra show very strong peaks at MeV energies (Blom et al. 1995, Bloemen et al. 1995). It is clear that two spectral components can be identified in such type of sources, the MeV peak and close to the power law spectrum extending through the EGRET energy range (Kanbach 1996). The spectrum of the most prominent source of this type is variable with the spectral index in the EGRET energy range changing from 1.67 ± 0.12 to 2.24 ± 0.36 (Blom et al. 1996) and shows a cut-off at a few GeV (Kanbach 1996).

These observations are often interpreted in terms of the e^\pm pair annihilation in a jet model (e.g. Marcowith et al. 1995, Roland & Hermsen 1995, Böttcher & Schlickeiser 1996, Skibo et al. 1997). However Sikora & Madejski (1996) argue that this model can not explain the MeV excesses since jets are optically thin and the e^\pm pair annihilation is not efficient. The annihilation model has also serious problems with explanation of the recent observations of 3C273 (McNaron-Brown et al. 1997). The spectrum of 3C 273 shows clear break at ~ 0.3 MeV which is inconsistent with the blueshifted e^\pm annihilation line in a jet. Motivated by this problems, Sikora & Madejski (1996) proposes that the MeV bump is produced by second population of electrons with energies ~ 100 MeV present in the jet.

Recently we have proposed another possible explanation of these intriguing observations (Bednarek 1997b). Let us consider the general scenario in which electrons are accelerated in the jet either rectilinearly in small regions along the jet (Bednarek & Kirk 1995, Bednarek et al. 1996a,b) or quasi-isotropically in a shock moving through the jet (e.g. Dermer & Schlickeiser 1993, Sikora et al. 1994, Blandford & Levinson 1995). Relativistic electrons can inverse Compton scatter soft radiation coming from a thin accretion disk (as considered by Dermer & Schlickeiser 1993 and Bednarek et al. 1996) or from a thick accretion disk (Melia & Königl 1989 and Bednarek & Kirk 1995). However if the disk geometry changes from the thin one (in the outer disk part) to the thick one (in the inner part) then this same population of electrons can produce strong peak at MeV energies (or below), by scattering the radiation of a thick disk. Close to a power law type spectrum extending above a few tens of MeV through the GeV energy range, originates at further distances along the jet as a result of scattering the radiation of the thin disk. By changing only the acceleration efficiency along the jet (keeping constant the disk parameters) we are able to fit very different spectra of PKS0208-512 observed during two periods: May - June 93, and July 91 - Jan 92. The cut-off in the spectrum observed from this source at a few GeV is explained by the lack of saturation of electron acceleration by the ICS energy losses at further distances along the jet. At such distances electrons are injected into the jet with the maximum possible energies gained from acceleration regions and lose energy mainly on synchrotron mechanism in random component of the jet magnetic field.

Two types of the soft radiation field, through which the relativistic jet propagates, can be also identified with the direct disk radiation and the quasi-isotropic radiation, reprocessed by the matter surrounding the accretion disk. These two radiation fields has been discussed separately in earlier models.

5. Conclusion

The γ -ray observations of blazars have given us unique inside into the energetic processes occurring within central parsec of active galaxies. They put already very strong constraints on possible theoretical interpretations. Only a few general pictures made an effort to incorporate in a consistent model the variety of reported observational features like, very short time scale variability, different types of blazars (MeV, GeV, TeV), emission extending up to at least ~ 10 TeV. In my opinion such a picture is given in papers which discuss the general model proposed initially by Dermer, Schlickeiser & Mas-

tichiadis (1992) (and developed by Dermer & Schlickeiser 1993, 1994; Böttcher & Schlickeiser 1996; Böttcher, Maue & Schlickeiser 1996; Skibo, Dermer & Schlickeiser 1997; Dermer, Sturmer & Schlickeiser 1997), or the model considered by Bednarek & Kirk (1995) (and developed in Bednarek, Kirk & Mastichiadis 1996a,b; Bednarek 1997b). Such complementary description can be found in the model proposed by Sikora, Begelman & Rees (1994) (see also, Sikora & Madejski 1996; Sikora, Begelman & Madejski 1997). Some new ideas has been also investigated recently. They base on a less popular fast jet model (Bednarek 1997a, Bednarek & Protheroe 1997d), or propose that γ -rays may originate during collisions of compact objects (clouds, massive stars, supernova shocks or supernova debris) with the jet plasma (Dar & Laor 1997; Bednarek & Protheroe 1997a; or by Bednarek in this paper). The simultaneous spectral information obtained recently at different energy ranges (although not yet completely satisfactory) suggests that the processes occurring there may be more complex than considered previously. It will be not surprising if a few different radiation mechanisms, possibly operating at different locations are needed in order to explain the observations. They suggest also that the inner jets in blazars may be much faster than supposed previously based on the radio observations. Their Lorentz factors can be as high as ~ 100 which is consistent with the observations of intraday variability in some AGNs (Begelman et al. 1994).

It is likely that part of particles, accelerated in the jet, can be trapped inside the host blazar galaxy. This hypothesis can be checked by deep observations of nearby radio galaxies which are supposed to be misdirected blazars (e.g. Cen A, Morganti et al. 1992). In fact the closest radio galaxy, Cen A, may be an example of such type of γ -ray source already detected by the EGRET telescope.

The real progress in understanding the γ -ray emission mechanisms in blazars would be done with the detection (or non-detection) of the neutrino signals from these objects with the power comparable to their γ -ray power. This would decide about importance of the hadronic processes in blazars considered by a few models (e.g. Mannheim & Biermann 1992, Bednarek 1993, Coppi et al. 1993, Protheroe 1997, Bednarek & Protheroe 1997d). Some models (Bednarek 1997, Bednarek & Protheroe 1997d) suggest, moreover, that only FSRQ blazars (GeV blazars) may emit neutrinos and γ -rays, in contrary to BL Lac type blazars (TeV blazars) which may be sources of only γ -rays.

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